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ISSC COMMITTEE III.1. CHAPTER 2: DRAFT: "ULTIMATE STRENGTH: FUNDAMENTALS

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2.0 Fundamentals

The collapse analysis of structures is a very complex process involving elasto-plastic material behaviour, large displacements, instability of structural components and systems, and possibly dynamic response. Encompassing these various requirements into a numerical predictive capability for ultimate strength analysis of marine structures is a challenging task, one that has received considerable attention in the research community over the past several years. There have been several proposed approaches, all with some varying degree of approximation, which have been extensively discussed in previous Committee III.1 reports. This chapter continues to discuss developments in the fundamentals of collapse analysis with emphasis on the finite element method, which is a fundamental component of most of the ultimate strength analysis methods and, on reliability methods, which are being adopted into ultimate strength calculations.

2.1 Material and Fabrication Effects

High strength steel is becoming more common in ship and offshore construction and the material properties and overall behaviour of these steels have some significant differences from those of traditional mild constructional steel. Box (1994) discusses the properties of high strength steel in the context of ship design while Dier and Whillock (1994) examine the suitability of existing design criteria to handle high strength steel designs. A reliability investigation is undertaken to assess the influence of yield to tensile strength ratio on component design. Design for ultimate strength needs to consider the post-yield behaviour of steels, in particular the hardening rate and ductility in addition to the yield stress and tensile strength values.

Using nonlinear material models within the context of a numerical finite element analysis is addressed by Nho and Kim (1993) who include large strain and material damage effects. This work is continued by Nho et al. (1994) who develop an elasto plastic-damage model.

Ship and offshore structures are predominantly welded structures, however; the number of studies on the ultimate strength of welds with realistic defects is surprisingly small. Dexter and Ferrell (1995) provide data and analysis to support the acceptance of undermatched butt welds in high-strength steel in shipbuilding. They observed no consistent differences between the ultimate strength results of the moderately-undermatched welds and the overmatched welds. Bannister and Harrison (1995) investigated the same issue on a range of structural steels. They demonstrated that the behaviour of parent material wide plate tests and wide plates tests on welded plates of mismatched strength can vary widely depending on the stress-strain characteristics of the material. In some circumstances the stress-strain characteristics of the parent material may dominate any effect of weld strength mismatch.

Increasing use of structural reliability methods results in a demand for stochastic description of material properties, however collection and analysis of new stochastic data has not received much attention during the review period. Proceedings of the previous ISSC (ISSC94-III.3) give stochastic data regarding yield stress, tensile strength and Young's modulus for mild, higher tensile and high yield steels. Buglacki (1996) investigates HSLA steel grades 420-690. Typical distributions of mechanical properties and carbon equivalent of quenched and tempered high strength steel plates for offshore application, BS7191: 450EM/EMZ are shown in Figure 1[British Steel, 1993].

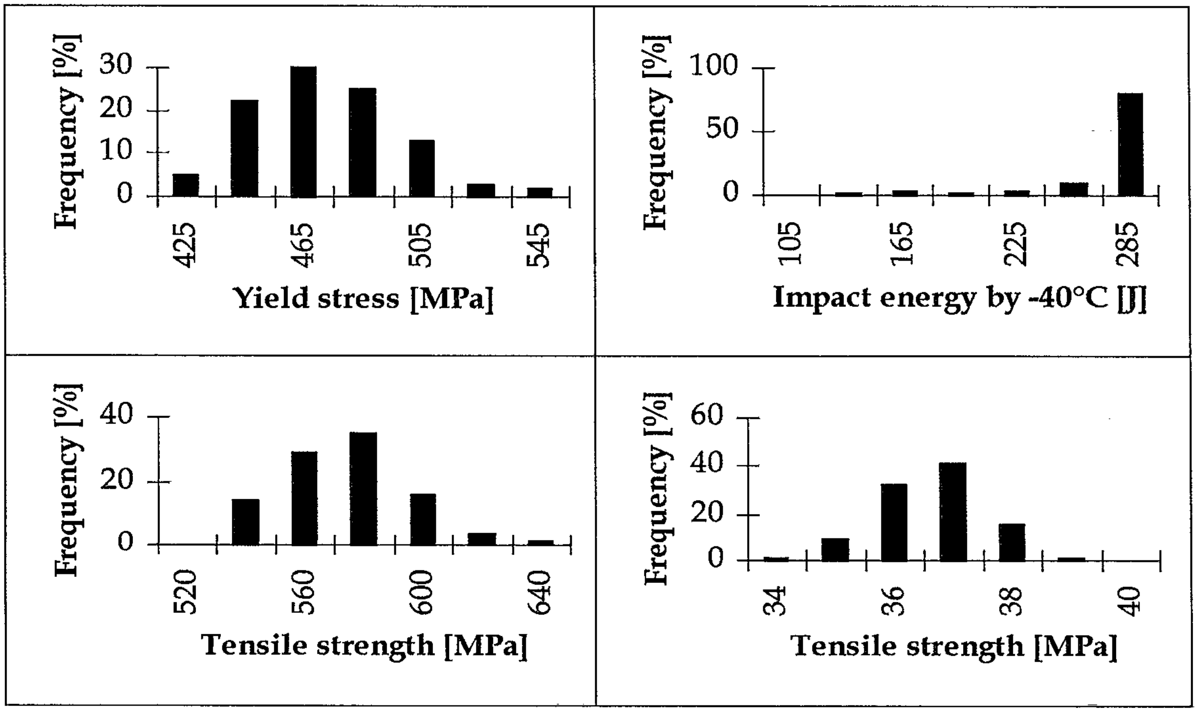

Figure 1. Typical distributions of mechanical properties and carbon equivalent of quenched and tempered high strength steel plates for offshore application [British Steel, 1993].

Stochastic data regarding other structural materials and other properties is still scarce, old and/or missing.Vargel and Rhenalu (1996) examined the physical properties of aluminium alloys for Shah Khan et al (1994) address the material and testing aspects of damage tolerance under a range of environmental and loading conditions, and deals broadly with measurements of residual stresses within the structure.high speed vessels. Raynaud (1996) discusses some possibilities how to make the current aluminium alloys stronger. However, careless introduction of these alloys may lead to delayed failures during service.

2.2 Buckling Fundamentals (Elastic/Plastic)

Fundamental methods for determining the buckling capacity of structural components have not received much attention during the review period. Elastic eigenvalue calculations with knockdown factors and elasto-plastic nonlinear numerical collapse calculations remain the primary buckling load determination methods. The latter has received some attention with improvements in modelling specific details in nonlinear collapse. Shin and Kim (1995) investigate buckling collapse of plates in a biaxial compression/tension state where plastic compressibility and tensile stiffening are considered. The `reduced stiffness theory' is applied by Kawamoto and Yuhara (1993) to axially loaded cylinders to develop a relationship between initial imperfections and plasticity in collapse calculations. Comparison to nonlinear finite element calculations and experimental data show good results.

Orisamolu and Liu (1995) develop linear elastic buckling eigenvalue solutions within the context of stochastic finite element analysis using random field theory and FORM reliability analysis. The development of stochastic finite element methods holds considerable potential for future buckling and collapse analysis.

A method of improving nonlinear finite strip calculations of post-ultimate collapse behaviour of plating components is presented by Ashari and Bradford (1995). Bubble functions which describe internal displacement modes are used to augment the solution and produce faster convergence for imperfect plate assemblies.

There have been a number of works related to coupled instability concerning the interaction between buckling modes and in particular interaction between local and overall buckling failure. Gioncu (1994) examines coupling between local plastic deformation at the atomic lattice level and overall flexural buckling of a bar. Menken et al. (1994) refer to a case where the coupled buckling load of several local modes is lower than the first overall buckling mode. Ghersi et al. (1994) describe a series of tests involving local and lateral buckling.

A phenomenon described as `negative shear lag' is described by Machacek et al. (1994) who demonstrate that interaction between buckling and negative shear lag have opposite effects on the longitudinal stress distribution in wide flange box girders.

2.3 Plastic Hinges and Yield Lines

Kmiecik (1995) gives a comparative discussion of yield line theory with and without membrane effects against large and small deflection finite element analysis. The analysis is for laterally loaded plates with constrained boundaries where membrane effects are significant in establishing the ultimate load carrying capacity. He concludes that large deflection finite element analysis is required to get accurate results, with yield line theory including membrane effects giving useful conservative values. Small deflection finite element analysis and yield line theory without membrane effects effectively predict the initial formation of plastic hinges but are of little value in determining ultimate capacity.

Jang and Seo (1993) present a simplified method of determining the collapse load of simply-supported stiffened plates by individually calculating all of the possible failure modes. A plastic hinge line method along with a large deflection elastic Rayleigh-Ritz method are used to determine the various failure loads, the lowest of which is used as the ultimate collapse value.

2.4 Static, Dynamic and Cyclic Effects on Collapse

Ultimate collapse of marine structures is usually calculated in a static load and response condition. With the exception of failures due to improper vessel loading, actual failures will almost always occur with some degree of dynamic or cyclic load behaviour and response, usually in extreme sea conditions. Adding dynamic or cyclic effects to already complex collapse calculations is a considerable challenge but some work is being undertaken in this area as more powerful computational means become available. George and Fukuchi (1993, 1993b, 1994, 1994b) have produced a series of reports covering the dynamic instability of axially loaded shells. Small dynamic perturbations to equilibrium states can cause premature collapse and gives some explanation to differences between collapse load calculations and experimental data.

Pegg (1994, 1994b) uses nonlinear dynamic finite element calculations to investigate the buckling collapse of cylindrical structures due to impulsive lateral pressure loads. Combinations of large hydrostatic pressure combined with small impulses show the possibility of collapse at values less than the static pressure collapse load. Initial imperfections and material property modelling have significant effects on the results.

A finite difference based nonlinear procedure for the analysis of unstiffened and stiffened plates valid in the static and dynamic range and allowing for large deflection nonlinear material behaviour is presented by Caridis (1994).

Skallerud et al. (1995) discuss a test program on tubular joints where extensive low cycle fatigue cracking under extreme load events leads to severe reduction of the structural capacity of the joints. This is a subject worthy of considerable work as a combination of extreme storm events, low cycle fatigue failure and ultimately collapse of the marine structure is a very complex but very possible failure mechanism.

Kaminski (1992) produced a thesis undertaking a thorough investigation of the buckling collapse of deck components under cyclic compression loading. The effects of initial imperfections, loading and strain rate are investigated experimentally and analytically. The instantaneous character of the failure in extreme seas is considered and the overall consequences of these various factors on reliability analysis of deck failure is considered.

Yao and Nikolov (1992), Yao et al. (1993) and Yao et al. (1995) study elasto-plastic collapse of stiffened plates under cyclic loading. A nonlinear finite element solution is initially used, followed by the development of simplified beam-column model to predict the complex elasto-plastic cyclic response.

2.5 Numerical Procedures

This section has been subdivided to include specific discussions of numerical procedures related to reliability calculations of ultimate strength and of finite element methods. As mentioned in the introduction, there are several numerical procedures used to calculate the ultimate bending capacity of ship structures. These have been outlined in previous Committee III.1 reports, particularly in 1991 which gave a comparison of the various methods against the U.K. 1/3 scale frigate model test. Development and validation of these various methods continue.

Developments of new plate buckling elements for use in the Idealized Structural Unit Method (ISUM) are discussed in Ueda et al. (1993) and Ueda and Masoaka (1993). The former element has an improved post-ultimate strength algorithm to account for reduction in strength of plating. The latter element is a completely analytical formulation based on eigenvalues which will produce results for buckling and post-buckling of plates with a minimal solution time. Both ISUM elements compare favourably to finite element solutions.

Park (1992) describes a method of calculating hull girder ultimate strength for SWATH vessels in which shear lag and warping distortion effects are taken into consideration. The significant difference between this calculation and traditional ultimate strength calculations is the assumption that plane sections do not remain plane.

Yao and Nikolov (1994) describe a method for hull girder collapse using elasto-plastic collapse analysis of stiffened plate including stiffener tripping. They show that stiffener tripping significantly reduces the ultimate strength of the stiffened plate component and the hull girder.

2.5.1 Procedures Involving Reliability Methods

Ultimate strength has been investigated as a limit state in structural reliability calculations for ship structures. This has been primarily done at the component failure level where closed form solutions to plate failure are available for limit state formulation. Hughes et al. (1994) undertook a U.S. Interagency Ship Structure Committee (SSC) study on determining uncertainties associated with ship strength. A discussion of types of uncertainties and methods for determining uncertainties is given followed by a comprehensive discussion of compressive collapse of stiffened panels. Two failure modes of stiffener-induced and plate-induced collapse of stiffened panels following the U.K. BS5400 procedure for design of box girders (also suitable and used for ship design) are studied with respect to available experimental data. Bias and coefficients of variation are derived from the limited data sets and ranking of importance of various parameters is given.

Mansour and Hovem (1994) discuss reliability analysis of ultimate strength in conjunction with a demonstration of reliability methods for ship structures also undertaken for the SSC. Various means of calculating hull girder or component ultimate loads are used in conjunction with a simple limit state of ultimate moment with stillwater and wave induced applied moments. Derivation of extreme load events are based on specified storm return periods. Modelling uncertainties are assigned to the ultimate, stillwater, wave and slam induced bending moments. The Marine Structures paper by Mansour and Wirsching (1995) discusses further SSC related work where sensitivities of the means and coefficients of variation are evaluated, as well as importance factors which relate the sensitivity of the reliability index to the limit state parameters. Calculations are carried out for two U.S. Navy cruisers, a double-hull tanker and an SL-7 containership. The buckling knock-down factor (also modelling error) was found to be the most significant parameter in the ultimate strength calculations for all ship types. The slamming induced bending moment was found to produce the smallest effect on safety of the three load parameters.

Qing et al. (1995) derive a probabilistic model of structural redundancy to determine the residual longitudinal strength of damaged ship hull structure. Analytical models of damage are used in this study. Kim and Yang (1994) produce a sensitivity analysis of stochastic imperfections in cylindrical shells under static loading. Relationships between reliability index and load, and reliability index and safety parameters are determined.

2.5.2 Finite Element Methods

Finite element methods, in some form, continue to be an essential tool in ultimate strength assessment. The availability and increasing robustness of nonlinear finite element solutions has led to their use either directly in collapse calculations or as benchmarks for more approximate methods. It is beyond the scope of this report to summarize all relevant work in nonlinear finite element methods over the past three years. Discussion will be limited to only a few works which are directly related to marine structures.

Nonlinear finite element analysis still retains a degree of `art' in producing viable solutions. Knight et al. (1995) discuss the effects of various element formulations and solution algorithms for finite element solutions on collapse of cylindrical shells. Murotsu et al (1995) develop a specialized finite element which models yield and collapse behaviour of ship structural panels. This is combined with reliability methods to examine component and system failure in ship structures. Identifying the critical path of component failures for system failure proved to be an important consideration in identifying overall collapse probabilities. Lee et al. (1993) develop degenerated shell and eccentric beam elements with specialized degrees of freedom to model local beam failure. Results prove to be more effective than modelling beams with shell elements.

Briassoulis (1995) describes the development of a shell element which has no spurious energy modes and does not suffer from any element `locking', a problem existing in many shell elements which results in unconservative estimates of structural stiffness. Katsikadelis and Kandilas (1995) produce a hybrid method for plate analysis by combining aspects of finite element, boundary element and finite difference methods into an `Analogue Equation Method'.

Wook and Tae (1992) describe the development of a large displacement beam element and Ronagh and Bradford (1994) review finite element modelling of lateral buckling of beams and derive a new set of degrees of freedom which can take this mode of failure into account. Toi and Isobe (1993, 1994) describe the development and use of a cubic beam element which employs shifting of the integration points to improve the solution accuracy and speed. Elasto-plastic buckling and dynamic collapse calculations for framed structures are carried out.

Summary and Recommendations from Chapter 2

There has been considerable progress in collapse analysis of structures involving elasto-plastic material behaviour, large displacements, instability of structural components and systems, and dynamic response. Encompassing these various requirements into a numerical predictive capability for ultimate strength analysis of marine structures is a challenging task. The effects of materials and fabrication effects is fundamental in collapse analysis but has thus far received little attention in practical buckling collapse analyses. The committee recommends investigations on the performance of fillet and butt welds in shear and of the potentially harmful effects of welding residual stresses on ultimate strength. Efforts in data collection and stochastic analysis of material properties including their possible correlation and their dependence on strain rate and temperature are also required.

The finite element method still remains the primary tool for calculating elasto-plastic collapse of structural components although there has been progress in developing simplified methods for specific problems. There has been considerable work done in cyclic loading and dynamic effects on collapse of components and as computing power becomes greater this topic will likely be expanded to provide some practical methods of including dynamic effects in design. This will be an important step forward as most collapse events in ship structures occur during a cyclic load event usually involving dynamic aspects. Reliability methods continue to be studied for ultimate strength collapse. Efforts to calibrate methods against test data and establish uncertainties and biases for design are required.

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